
Chip formation studies in machining fibre reinforced polymer composites

A.I. Azmi

Centre for Advanced Composite Materials (CACM),
Department of Mechanical Engineering,
The University of Auckland,
Private Bag 92019, Auckland, New Zealand
E-mail: aazm007@aucklanduni.ac.nz
and
School of Manufacturing Engineering,
Universiti Malaysia Perlis,
06000, Kangar, Perlis, Malaysia
E-mail: azwaniskandar@unimap.edu.my

Abstract: The use of end milling process for machining of fibre reinforced polymer composites has been widespread in various industries. Until recently, very little work has been reported with regard to characterisation of chip formation mechanisms while end milling these composite materials. This paper reports such study which was accomplished via high speed photography and quick stop procedure. It is apparent that the heterogeneity and insufficient ductility of the composites have produced discontinuous and fracturing chips. Information disclosed by the high-speed photography footages has shown that a layer of delaminated chip was formed as the tool cutting edge fractured the workpiece along the fibre orientation at the lowest cutting speed. The increased cutting speed accelerates the fracture of chips into smaller segments, which make it difficult to denote any chip formation processes. Similarly, shorter chip fragments were created as the tool cut at different fibre orientation (45° and 90° with respect to tool feed direction).

Keywords: machining; end milling; chip formation; fibre reinforced polymer composites.

Reference to this paper should be made as follows: Azmi, A.I. (2013) 'Chip formation studies in machining fibre reinforced polymer composites', *Int. J. Materials and Product Technology*, Vol. 46, No. 1, pp.32–46.

Biographical notes: A.I. Azmi is working as a Lecturer in the School of Manufacturing Engineering at Universiti Malaysia Perlis, Malaysia. He received his BSc in Mechanical Engineering from Purdue University, in Indiana, USA and MEng in Advanced Manufacturing Technology from University Teknologi Malaysia. He is pursuing his PhD at The University of Auckland, New Zealand. He has contributed several research articles in journals and international conferences in the area of composites machining.

1 Introduction

The study on chip formation during machining operation has served a pivotal role on fundamental insights into the mechanics of material removal. Hitherto, this study has proven to be effective for materials' machinability evaluations and has received considerable attentions among researchers. Two well-known theories with regard to chip formation for metal cutting, namely 'the adiabatic shear theory' and 'the crack theory' (Ning et al., 2008) have been regularly used to analyse the primary shear or deformation zone. However, it is imperative to note that the nature of the chip formed is not only associated to the changes in the shear zone. Material properties, which include ductility, hardness, thermal conductivity, and microstructures, also highly govern the chip forming mechanisms. In addition, Ning et al. (2008) asserted that undesirable phenomena such as instabilities during cutting process and deterioration of tool sharpness could alter the chip formation process quite significantly.

Unfortunately, chip formation study while machining fibre reinforced polymer (FRP) composites is often difficult due to their in-homogeneity and pronounced anisotropy. Added to that, these materials exhibit very little plastic deformation or if any at all, compared to that of homogenous and ductile materials (Sheikh-Ahmad, 2009). Obviously, the chip formation theories explained for metallic materials may not be appropriate to describe the mechanics of chip creation during machining of the FRP composites. Various types of fibre reinforcements and their architectures also limit any conclusive or generalise theories associated to the chip formations for these composite materials.

Nonetheless, these do not imply that their chip formation studies are less attractive compared to the metals. As a matter of fact, the earliest research efforts on the examination of chip formation during machining of FRP composites were reported by (Koplev et al., 1983; Arola et al., 1996; Bhatnagar et al., 1995), back in the mid-1990s. Both Koplev et al. (1983) and Arola et al. (1996) asserted that chip formations consist of a series of fractures which create highly diverse fragments of fibres and matrix materials. As expected, machining parameters essentially affect the types of chip being formed; e.g., sizes and shapes. Adding to that, fibre direction or orientation, also strongly influence the nature of chip; as highlighted in Arola et al. (1996), Bhatnagar et al. (1995), and Puw and Hocheng (1998).

In all of those reported studies, the 'quick stop' method, which has been developed for the metal cutting, was employed for the 'in-situ' microstructure analysis of the formed chip. This is despite the dissimilarity in the chip formation mechanisms between metal and FRP composites. It is well known that a quick stop device (QSD) is an established tool which is commonly used for fundamental study on chip formation during metal cutting. This device arrests a machining operation by rapidly disengaging the cutting tool from the workpiece material or vice-versa. Therefore, this allows the extraction of resulting chip root, as its strains, for subsequent microscopic analyses.

Nonetheless, several researchers have claimed that there exists a tool-chip separation delay during the tool or workpiece retraction while the QSD is in operation (Pujana et al., 2008; Sutter, 2005). This delay, which is dependent upon the design of the employed device, may considerably alter the state of chip deformation. Hence, the results may not accurately represent the dynamic changes of the machining process. As a result, high-speed filming or photography provides an option or alternative to effectively study

the chip formation during a machining or cutting operation. Indeed, this was demonstrated by Komanduri and Brown (1981), in which they have successfully presented images of segmented chips during orthogonal cutting of the cold-rolled steel. Chip segmentation processes were recorded using a high speed camera at 3,300 frames per second (fps) for cutting speeds up to 55 m/min. The results have allowed them to conclude that the chip segmentation process was mainly attributed to the instabilities of the cutting process. The authors then verified the video photographic observations of chip formation with comprehensive microscopic studies of the chip root obtained from the QSD.

Until recently several researchers have also reported the effectiveness of using high-speed filming/camera to observe the chip forming process for various metallic materials (List et al., 2008; Pujana et al., 2008; Sutter, 2005). Notwithstanding this, it is worthwhile to note that the acquisition of quality pictures in high-speed photography requires compromise between recording speeds, image resolutions, adequate lighting, high contrast, depth of fields, and exposure time (Komanduri and Brown, 1981; List et al., 2008).

On the other hand, very few studies in the past, have attempted a comprehensive characterisation of chip formations and morphologies while end milling glass fibre reinforced polymer (GFRP) composites. Hence, this paper reports on such study. The setup of high-speed photography, which consists of a high speed video camera in conjunction with a high-intensity lighting, has been employed for this purpose. This high-speed photography is used in order to observe the dynamic or phenomenological changes on the nature of chip formed during cutting operation of these composite materials.

Meanwhile, there has been limited information with regard to a QSD for interrupted machining operation such as milling. One such study was reported by Kovac and Sidjanin (1997). However, the detailed discussion about the construction of QSD cannot be found, which could question the results presented. Due to the unavailability of any QSD for milling operation, the current study has developed an apparatus/ setup to perform the quick stop procedure. This setup allows the end mill cutter to be frozen instantly, thus, which preserves the uncut chip on the workpiece material. Subsequently, microscopic analyses were performed on the chip root to characterise the nature of chip segmentations and morphologies.

2 Experimental setup

The chip formation studies in this paper have been accomplished using experimental setup and machining parameters discussed as follows.

2.1 End milling experiments and cutting parameters

The use of CNC milling centre for high-speed photography of chip formation for the composite materials was initially found to be problematic. This is mainly due to the space limitations on the CNC machine to position the camera at the optimum angle in order to capture the chip forming process. Hence, it was decided to use the conventional vertical milling machine, MAXIMART, which offers more space and flexibility on the video camera placement. This machine has a spindle power of 2.2 kW and the maximum spindle speed of 2,800 RPM. The uncoated tungsten carbide end mill tool was used for

the study herein. Machining parameters for the chip formation studies are given in Table 1. Such selection of machining parameters can be justified by three reasons:

- to alleviate the effect of tool wear during the cutting process
- to facilitate the preservation of unbroken chip during quick stop procedure
- to ensure production of robust chip for subsequent microscopic analyses.

It is imperative to highlight that conducting the tests at normal operating or machining parameters has resulted in improper chip formation. This is due to the fact that, at the harsher machining parameters (e.g., spindle speed $> 1,000$ RPM), the chip experiences a significant increase of strain, which intensifies fracture failures. As shown in other previous studies, the chips were mainly dusts of micro-sized particles due to the high strain applied to the workpiece material under the employed machining parameters. Unfortunately, this type of chip reveals very little information about the chip forming processes. Hence, the machining parameters were lowered so that desirable chips can be produced to facilitate further microscopic examinations. These parameters are given in Table 1.

Table 1 Machining parameters for chip formation studies

Workpiece material	Uni-directional GFRP composites
Tool	Single flute K20 end mill cutter 12 mm diameter
Machining parameters:	
Spindle speed, N	100, 300, 500 RPM
Linear effective speed, v	3.77, 11.30, 18.84 m/min
Feed rate, f_r	0.32 mm/rev
Axial depth of cut, d_a	3 mm
Radial depth of cut,	0.5 mm
Fibre orientation, A	$0^\circ, 45^\circ, 90^\circ$

2.2 High-speed photography settings

Two essential elements for a high quality image acquisition during the high-speed photography often compose of:

- 1 high speed camera
- 2 lighting.

Machining parameters can be set at high levels during the setup in order to take the advantage of the high-speed camera capabilities. However, larger sampling size, short exposure time, and high-intensity of light on the viewing area will then be essential. Besides, to study the details of the cutting process, the image of the subject of interest need to be magnified quite considerably. This, in turn, requires an increase in the depth-of-field which will compromise on the aperture settings, lens focusing, and consequently the intensity of the light. Hence, in this study, a high-speed video camera, the Phantom V210, having maximum recording speed of 300,000 fps and a full resolution

(1,280 × 800) recording capability of 2,000 fps, has been used for filming of the chip formation. A well-focused footage of the cutting zone in the present investigation has been achieved using two-COOLH Dedocool tungsten head lights. These lamps provide a high-intensity concentrated light on the interested viewing area. The general setup for this experiment is depicted in Figure 1.

Figure 1 General setup on milling machine consisting of (a) high speed video camera and (b) high intensity headlight (see online version for colours)

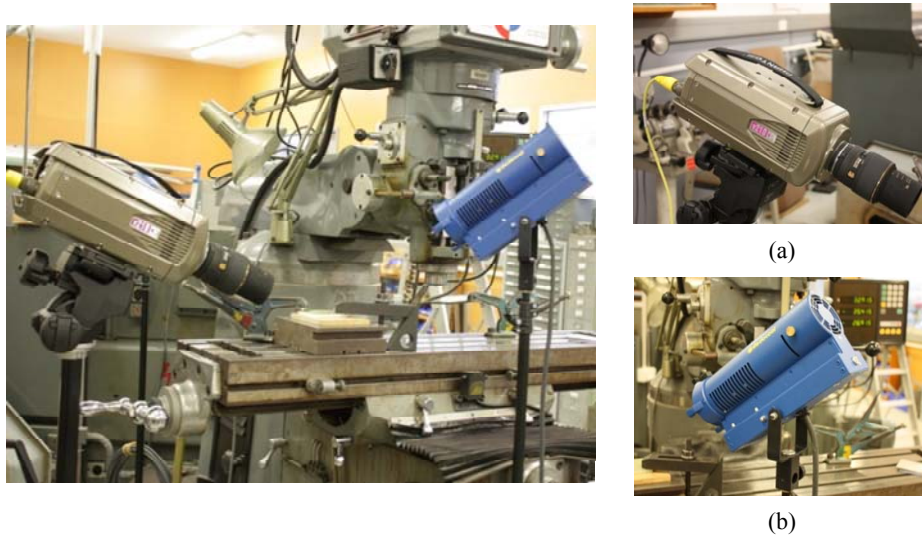
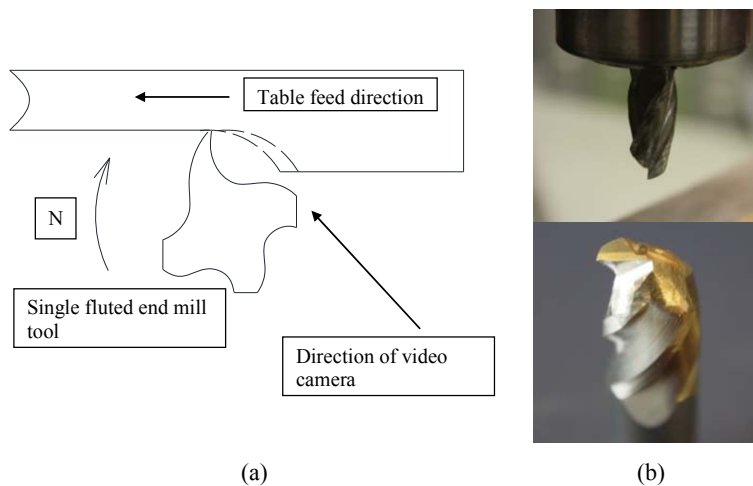


Figure 2 (a) Up milling of GFRP for filming of chip formation process and (b) Modified end mill cutter (see online version for colours)



It is literally known that end milling is a three-dimensional (3D) cutting process which involves a complex oblique cutting operation on the workpiece material. Due to helical geometries of the end milling cutter, the view of the cutting zone may be obstructed whenever machining is performed with full immersion of the cutting tool into the workpiece material. Therefore, to facilitate the viewing of chip formation during cutting operation, side end milling process (with up milling configuration) of the workpiece material has been chosen, Figure 2(a). It is to note that three out of four cutting flutes were also purposely ground to ensure that the interested cutting zone was not blocked by the progressing cutting flute. Figure 2(b) depicts the modified end mill cutter. Radial depth of cut, d_r , of 0.5 mm has been selected for this side end milling process. Meanwhile, under the set of cutting parameters employed, the chip formation process can be best captured at the 640×480 pixels resolution with recording speed of 1,000 to 3,000 fps.

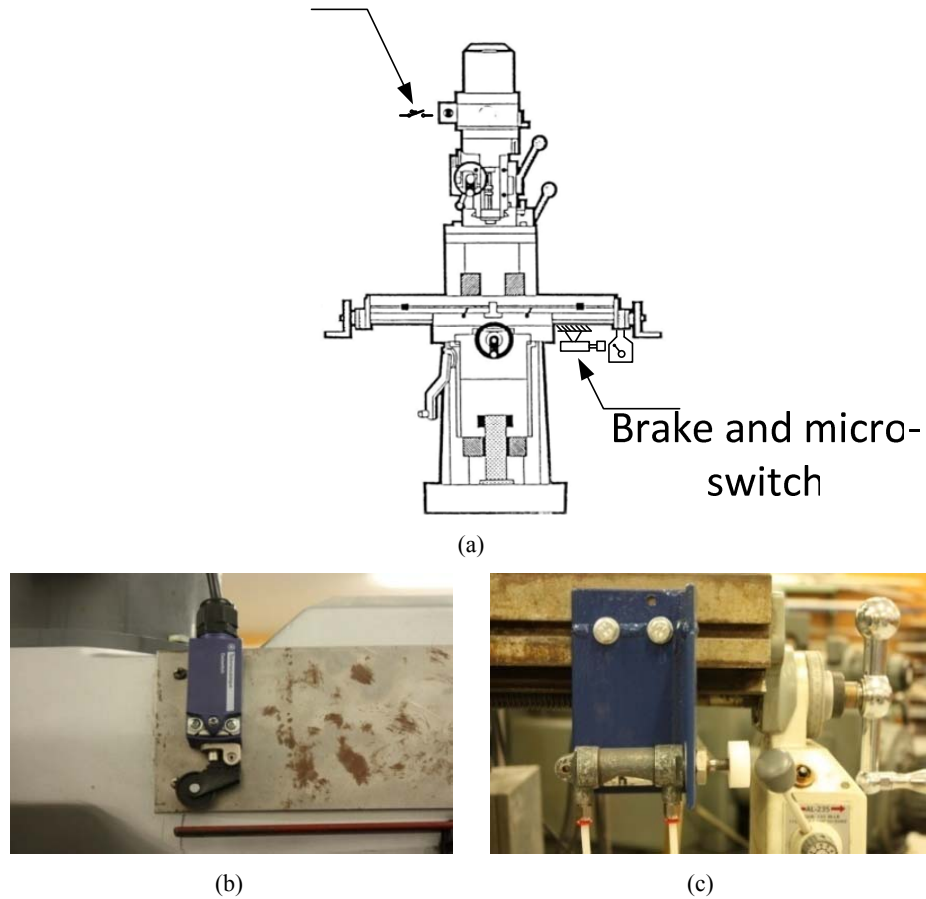
2.3 Quick stop arrangements

The working principle of the common QSD is through arrangement of shear pin, which is broken via impact, to consequently allow rapid separation of the tool from the cutting zone. Explosive charges are normally used to break the shear pin, accelerating the tool away from the cutting coupon. This design would be easily implemented under orthogonal cutting or turning processes which uses a single point tool. Unfortunately, the use of this device for milling process would be impractical, if not impossible due to intermittent cutting nature of milling operation. The ideal instant separation of the cutting tool from workpiece material would not be practically achievable in milling as it does in turning operation.

In fact, the rapid movement and interruption of either the workpiece material or the cutting tool, while preserving the chip on the GFRP workpiece could be very challenging. This is because the uncut chip may possibly or easily be broken-off due to the properties of the composite materials. Hence, this section elaborates on the effort to setup an arrangement; which enable the preservation of an uncut chip on the GFRP composites while cutting is in operation. The method employed herein is different from that of the common QSD used in orthogonal cutting or turning operation. In general, it involves a simultaneous halting of tool rotation and table feed via configuration of a tripped switch, braking system, and a pneumatic ram, Figure 3.

Basically, the OSISWITCH (tripped switch), which was fitted on the milling machine as shown in Figure 3(b), serves as the electrical switch to break/cut off the power on the machine during operation. This tripped switch was simultaneously triggered as the force is applied on the brake lever to stop the tool from continuously rotates. At the same time, the switch also sent a signal to the controller box to activate the fitted pneumatic ram, Figure 3(c). The movement of the ram then pushes on the feed table lever to disengage the feed table gear. The disengagement of feed table gear ensures that the motion of table feed was instantaneously halted. Each of these configurations is shown in Figures 3(b) and 3(c).

Figure 3 (a) Quick stop arrangement on the milling machine (b) The fitted trip switch and (c) Pneumatic ram (see online version for colours)



3 Results and discussion

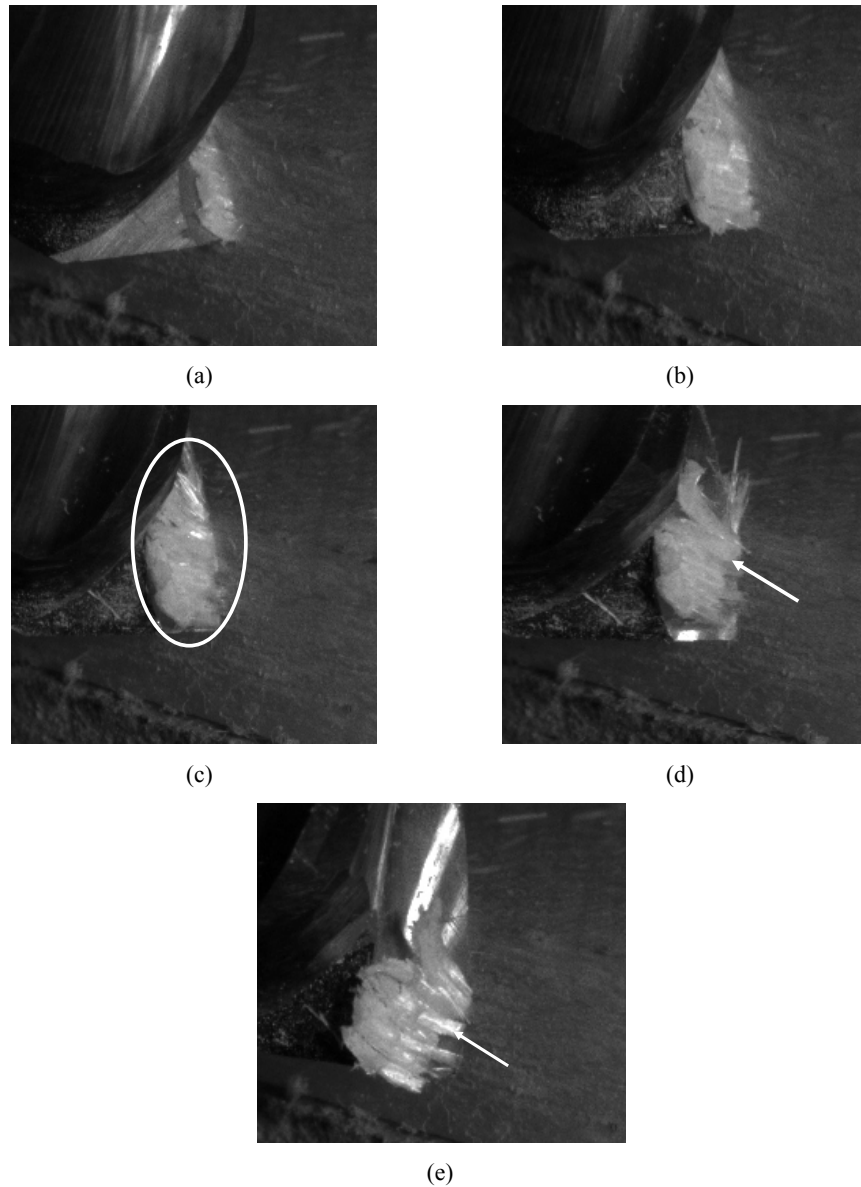
3.1 Results from high speed camera

3.1.1 Effects of cutting speed on chip size

Figure 4 presents photographic frames of chip formation recorded using the setup discussed earlier and under the tool rotational speed of 100 RPM with feed rate of 0.32 mm/rev. In general, information disclosed by the high-speed photographic footages show that a fairly defined chip can be formed as the tool cutting edge sheared along the fibre orientation, Figures 4(a) and 4(b). A layer of delaminated chip was observed to be peeled up along the tool rake face prior to the bending and buckling-induced fracture as the tool exits the workpiece material, Figure 4(c). Apparently, the chip has shown a little tendency to curl up along the rake face due to the helical nature of the tool. However, the lack of sufficient ductility on the GFRP composites restricted further deformation process

of the chip, as expected. As the tool disengaged from the workpiece material, appearance of the chip-ends reveals some evidence of fibre pull-out and delamination, as shown by the arrow in Figure 4(e).

Figure 4 Video footages during chip formation of side end milling GFRP composites at $N = 100$ RPM, $f_r = 0.32$ mm/rev and $A = 0^\circ$

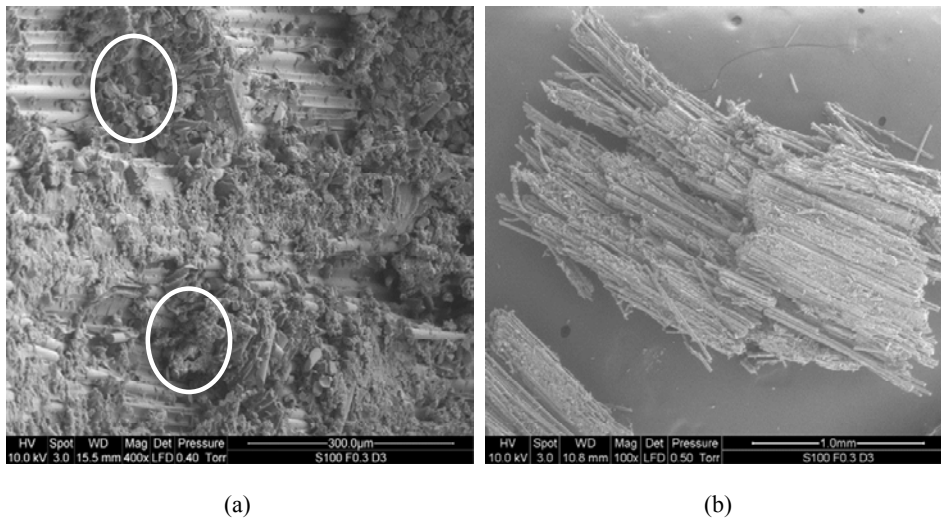


Judging from these photographic images, the features of the formed chip confirm to be the 'Mode/Type I' chip formation during orthogonal cutting of FRPs composites proposed by previous researchers (Arola et al., 1996; Wang et al., 1995). 'Mode I' chip

formation is defined as the fracture of a chip which propagates along the fibre-matrix interface as the chip undergoes shear. According to Arola et al. (1996), at one point during cutting, the chip is released due to bending failures. Although, these static images may not truly represent the dynamic changes of the chip; however, they are more or less reveal the information. Evidence from these video footages also exhibited the absence of plastic deformation during machining of GFRP composites in all of the cases considered herein.

Scanning micrographs of the machined sample substantiate the aforementioned buckling and bending induced fractures of the fibre reinforcement on the machined surface, Figure 5. The fractures seem to occur ahead of the cutting edge and perpendicular to fibre direction. Appearance on the machined surface and individual fibres distinctively shows the evidence of bending failures and delamination due to the action of tool cutting edge, shown by the ovals in Figure 5(a). In fact, the segment of fragmented chip collected clearly reveals that the fibres have been being pull-out from the GFRP workpiece, as depicted by the arrows in Figure 5(b). This leaves behind irregular or rougher machined surface, Figure 5(a). To some extent, this concurs to the surface roughness results obtained under the employed machining parameters discussed earlier in Azmi et al. (2012).

Figure 5 SEM images of machined surface and segmentation of chip collected at fibre orientation, $A = 0^\circ$ and $N = 100$ RPM, $f_r = 0.32$ mm/rev



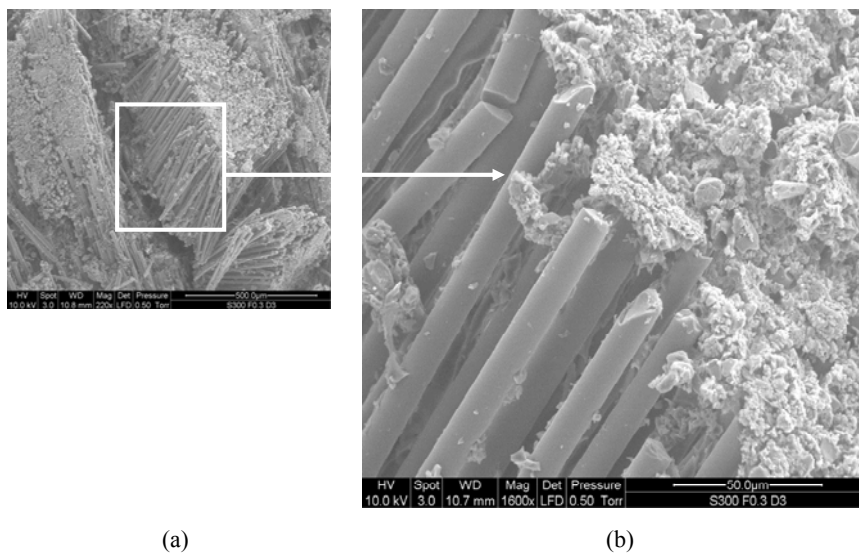
The increased cutting speed of 300 RPM and 500 RPM have caused the chip to be fractured chip or broken-off into smaller segments even before the tool disengaged from the workpiece material, Figure 6. This process is augmented through the high stress/load exerted by the rotating cutting tool on the chip surface at the elevated speed. Insufficient adhesive strength between epoxy matrix and the fibre reinforcements could likely be contributed to the splitting of the chip into smaller segments. It also appears from the microstructures of the collected chip that the fibre reinforcements were partially de-bonded from the polymer matrix, as depicted in the white colour box, Figure 7. As apparent, debris of epoxy matrix is seen to accumulate on the top surface of the fractured

fibre reinforcement as a result of epoxy matrix brittle fracture, which left the fibres to be loose.

Figure 6 Video footages during chip formation of side end milling GFRP composites at $N = 300$ RPM, $f_r = 0.32$ mm/rev and $A = 0^\circ$



Figure 7 SEM images showing fibre-matrix de-bonding as a result of stress exerted on the chip by the cutting action



3.1.2 Effects of fibre orientation

The machining tests were extended to cutting at the 45° and 90° fibre orientation/angle (with respect to tool feed). The results show completely different phenomena than those discussed previously. Even under the lightest condition tested, the photographic frames of the cutting sequences reveal no distinct chip formation. Instead, as soon as the tool came into contact with the workpiece material, parts of the chip were observed to be shattered into powdery particles of fibres and epoxy matrix. As the cutting progressed, the rate and the number at which the segmental chips segregated into smaller size accelerate and also

stochastic in nature. Unfortunately, from the photographic frames of captured video shown in Figure 8, it was difficult to denote clearly the chip formation process due to the reduction of the chip size. It is worthwhile to note that the mechanisms observed from the images appear to be consistent with those documented in past research during orthogonal cutting of the FRP composites (Arola et al., 1996; Nayak et al., 2005; Wang et al., 1995). The authors asserted that these phenomena were attributed to the out-of-plane fracture of the fibre reinforcement. However, evidence from the video footages suggests that fracturing of the chip is predominantly due to crushing-compression of the progressing cutting tool on the workpiece material.

Figure 8 Chip segmentation under the machining parameters of $N = 500$ RPM, $f_r = 0.32$ mm/rev and $A = 90^\circ$

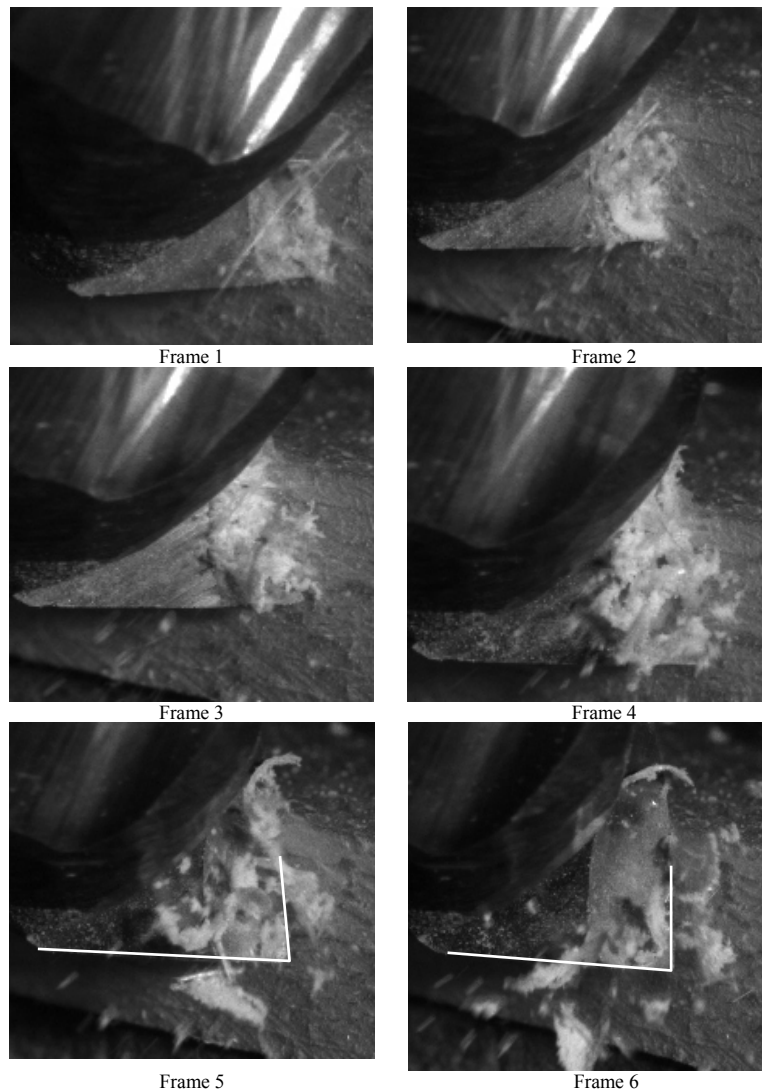
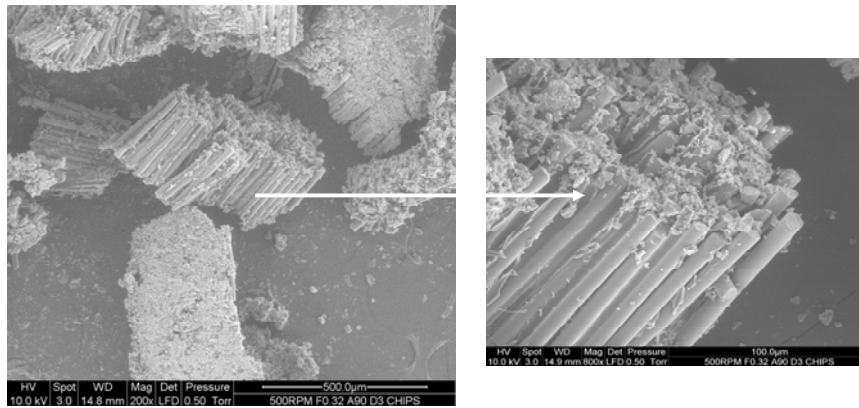
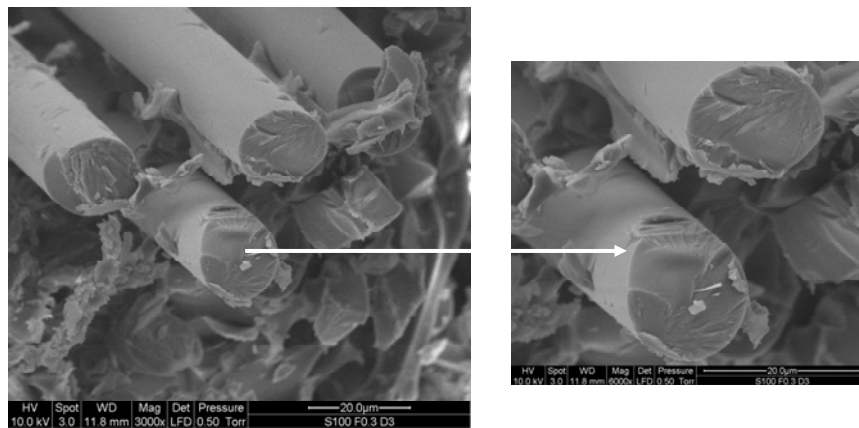


Figure 9 (a) SEM images of morphologies of the collected chip while cutting at 90° to fibre orientation, (b) Close-up of fractured fibres and (c) 'Sticking-out' of fibre from machined surface



(a)

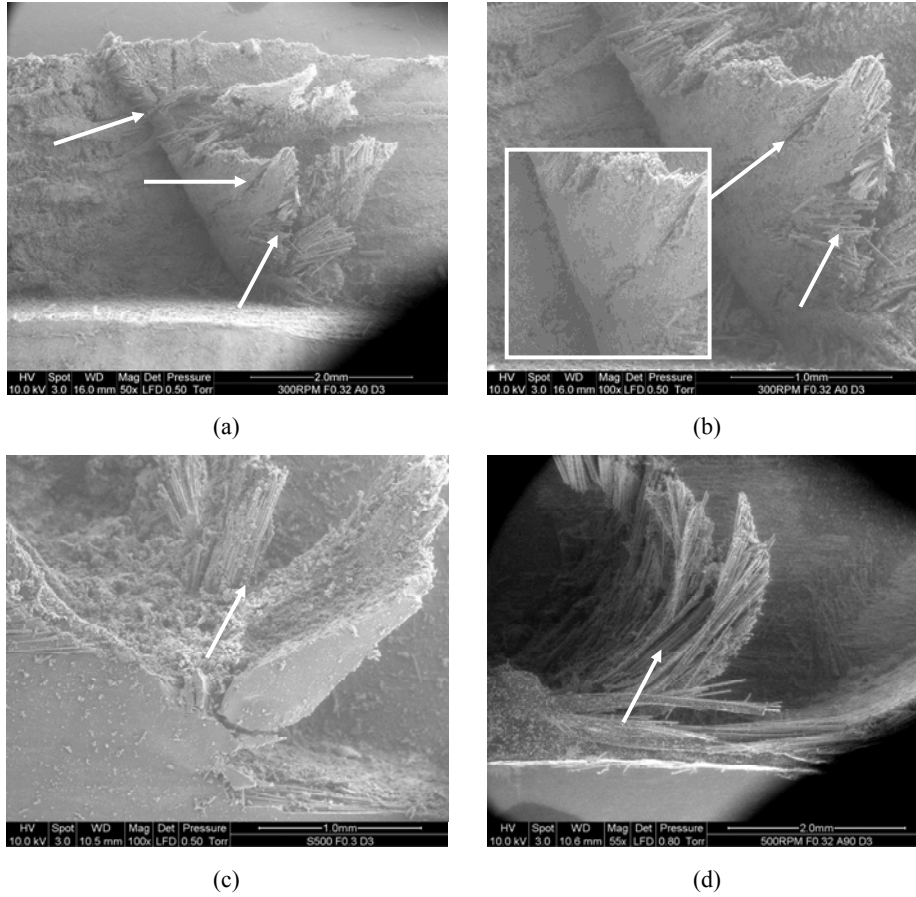


(b)



(c)

Figure 10 SEM images of chip root obtained from quick stop method for (a)–(b) $N = 300$ RPM, $f_r = 0.32$ mm/rev and $A = 0^\circ$; (c) $N = 500$ RPM, $f_r = 0.32$ mm/rev and $A = 0^\circ$ and (d) $N = 500$ RPM, $f_r = 0.32$ mm/rev and $A = 90^\circ$



Despite the random size of chips while machining at the 90° fibre orientation, the chips were carefully collected using a double side adhesive tape for subsequent microscopic studies. Clearly, one distinct feature of the chip is that the fibres are still being held by the epoxy matrix. As observed under the scanning electron microscope (SEM), Figure 9(a), the distribution of epoxy matrix is still intact within the fibre bundles. This could be likely due to the reduced length of the fractured chip that got separated from the tool rake face. As a result, the chip did not tend to curl or slide up the tool rake face during cutting. This curl or slide up effect may be one of the main causes for the brittle fracture of the epoxy resin as the tool exerts stress on the chip during cutting.

The appearance at the end vicinity of individual fibres reveals the bending and brittle fracture of the glass fibres which were subjected to shearing, tensile or bending stresses. It is evident that the fractured surface of the glass fibre appears to be smooth due to its amorphous and brittle nature, Figure 9(b). Morphologies of the fractured fibres also show that the bending and brittle failures occurred at random positions along the fibre directions. This created irregular machined surface with the fibre ends ‘sticking-out’ at varying lengths, Figure 9(c) (Sheikh-Ahmad, 2009). The direct contact between these

fibres and tool cutting edges is the major cause of abrasive wear on the cutting tool while machining these FRP composites as highlighted in Azmi et al. (2012).

3.2 Results from quick stop method

The unbroken or preserved chip on the machined surface obtained from the quick stop method was carefully cut out from the workpiece material. The samples were prepared and examined under SEM to acquire information regarding morphologies of the chip root. The typical microscopic photographs of the uncut chip are shown in Figure 10. As apparent, the preserved chip exhibits an oblique shearing of the chip material due to the cutting tool geometry. Parts of the deformed chip can be seen to be broken off from the bigger chunk of chip. Indeed, a closer examination on the back and remaining chip surface has shown crack initiation between the bonding of fibre reinforcement and epoxy matrix, depicted by the arrow in Figures 10(a) and 10(b). This crack promotes the splitting of chip into smaller segments as shown in Figure 10(c). Similar to that observed by Puw and Hocheng (1998), the compressive force exerted by the cutting tool compels the chip to fail due to bending and buckling, Figure 10(d). The failures were observed to be along the fibre direction and accompanied by considerable brittle fracture of the weaker epoxy matrix due to the high cutting speed employed. Hence, this matches the results obtained from the high-speed photography of chip formation discussed earlier.

4 Concluding remarks

The following concluding remarks can be made based on the results observed in the study herein:

- Insufficient ductility and non-homogeneous properties of the GFRP composites have produced discontinuous and fracturing chip during machining operation. Morphologies of the collected chip and machined surface revealed the bending, buckling, fracture, delamination, and crushing-compression of the fibre reinforcement and matrix material. The various modes of material failures or fractures seem to occur randomly along the machined surface.
- Under the lightest cutting speed tested, a layer of delaminated chip was seen to be peeled along the rake face of the cutting tool. However, an increased cutting speed has resulted into smaller chip segmentations. This was mainly due to the increased stress on chip surface and weak adhesive bonding between the fibres and the epoxy matrix.
- When cutting at 45° and 90° fibre orientation, the chips were observed to be shattered into powdery particles of fibres and epoxy matrix due to the out-of-plane fracture and crushing-compression of the progressing cutting tool on the workpiece material. These failures make it difficult to denote any chip forming mechanisms.
- Although the QSD designed can be fairly used to preserve unbroken chip during machining, its robustness can be further improved for future studies that involve high or harsher machining parameters.

References

- Arola, D., Ramulu, M. and Wang, D.H. (1996) 'Chip formation in orthogonal trimming of graphite/epoxy composite', *Composites Part A: Applied Science and Manufacturing*, Vol. 27, No. 2, pp.121–133.
- Azmi, A.I., Lin, R.J.T. and Bhattacharyya, D. (2012) 'Machinability study of glass fibre-reinforced polymer composites during end milling', *The International Journal of Advanced Manufacturing Technology*, in Press, available at <http://dx.doi.org/10.1007/s00170-012-4006-6> (accessed on 15 March 2012).
- Bhatnagar, N., Ramakrishnan, N., Naik, N.K. and Komanduri, R. (1995) 'On the machining of fiber reinforced plastic (FRP) composite laminates', *International Journal of Machine Tools and Manufacture*, Vol. 35, No. 5, pp.701–716.
- Komanduri, R. and Brown, R.H. (1981) 'On the mechanics of chip segmentation in machining', *Journal of Engineering for Industry*, Vol. 103, pp.33–51.
- Koplev, A., Lystrup, A. and Vorm, T. (1983) 'The cutting process, chips, and cutting forces in machining CFRP', *Composites*, Vol. 14, No. 4, pp.371–376.
- Kovac, P. and Sidjanin, L. (1997) 'Investigation of chip formation during milling', *International Journal of Production Economics*, Vol. 51, Nos. 1–2, pp.149–153.
- List, G., Nouari, M., Géhin, D., Gomez, S., Manaud, J.P., Le Petitcorps, Y. and Girot, F. (2008) 'Wear behaviour of cemented carbide tools in dry machining of aluminium alloy', *Wear*, Vol. 259, Nos. 7–12, pp.1177–1189.
- Nayak, D., Bhatnagar, N. and Mahajan, P. (2005) 'Machining studies of uni-directional glass fiber reinforced plastic (UD-GFRP) composites part 1: effect of geometrical and process parameters', *Machining Science & Technology*, Vol. 9, No. 4, pp.481–501.
- Ning, L., Veldhuis, S.C. and Yamamoto, K. (2008) 'Investigation of wear behavior and chip formation for cutting tools with nano-multilayered TiAlCrN/NbN PVD coating', *International Journal of Machine Tools and Manufacture*, Vol. 48, No. 6, pp.656–665.
- Pujana, J., Arrazola, P.J. and Villar, J.A. (2008) 'In-process high-speed photography applied to orthogonal turning', *Journal of Materials Processing Technology*, Vol. 202, Nos. 1–3, pp.475–485.
- Puw, H.Y. and Hocheng, H. (1998) 'Chip formation model of cutting fiber-reinforced plastics perpendicular to fiber axis', *Transactions of ASME*, Vol. 120, No. 1, pp.192–196.
- Sheikh-Ahmad, J.Y. (2009) *Machining of Polymer Composites*, Springer, New York, USA.
- Sutter, G. (2005) 'Chip geometries during high-speed machining for orthogonal cutting conditions', *International Journal of Machine Tools and Manufacture*, Vol. 45, No. 6, pp.719–726.
- Wang, D.H., Ramulu, M. and Arola, D. (1995) 'Orthogonal cutting mechanisms of graphite/epoxy composite. Part I: uni-directional laminate', *International Journal of Machine Tools and Manufacture*, Vol. 35, No. 12, pp.1639–1648.